Monthly Report No. 6

HYDROGEN-OXYGEN APS ENGINES

NAS 3-14354

Period Ending 28 February 1971

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I. PROGRAM OBJECTIVES

The primary objective of this contract is to generate a comprehensive technology base for high performance gaseous hydrogen-gaseous oxygen rocket engines suitable for the Space Shuttle Auxiliary Propulsion System (APS). Durability requirements include injector and thrust chamber designs capable of 50 hours of firing life over a 10-year period with up to 10^6 pulses and single firings up to 1000 sec. These technical objectives are being accomplished and reported upon in a twenty-one task program summarized below. The first ten tasks relate to high pressure APS engines, parallel tasks eleven through twenty relate to low pressure APS engines, and task twenty-one is a common reporting task.

Task Titles	High P_c Task	Low P_c Task
Injector analysis and design	I	XI
Injector fabrication	II	XII
Thrust chamber analysis and design	III	XIII
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Ignition system analysis and design	V	XV
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Pulsing tests	X	XX

Common Task

Reporting requirements XXI

During this report period, the program objectives were redirected toward providing an expanded high pressure program which would analytically and experimentally investigate the impact of lower temperature propellants (fuel = 150 to 600°R, oxidizer = 300 to 600°R). Work on Tasks XIV, XIX, and XX was halted by a

I, Program Objectives (cont.)

stop work order dated 11 February 1971, while the scope of work on Tasks XII, XIII, XVII, and XVIII was reduced to that compatible with closing out Low P_c activities in an orderly and documented manner.

Section II of this report provides a review of the progress in the eighth program month on the high pressure engine technology portion of this contract. Low pressure engine technical progress is covered in Section III.

II. HIGH PRESSURE TECHNOLOGY

A. PROGRAM PROGRESS

1. Task I - Injector Analysis and Design

No activity on this task.

2. Task II - Injector Fabrication

No activity on this task. Because of the good injector durability demonstrated in Task VIII, it was found unnecessary to complete fabrication of all of the injectors planned for this program. The injectors employed in Task VIII testing will be modified for use with cooled chambers in Task IX testing by modifying the fuel manifold to feed directly from the chambers. The residual funding from this task has been employed in Task VIII to conduct 15 more injector checkout tests than were originally planned and funded in the program.

3. Task III - Cooled Chamber Analysis and Design

Activities in this task involved evaluating Task VIII heat flux data and film coolant probe data obtained from copper chamber tests and adiabatic wall data as obtained from the film-cooled adiabatic wall chamber. The heat sink copper chamber, which was reinstrumented with 24 new gas-side thermocouples in the last report period, was employed for a major portion of this month's testing. Some of the thermal data were a repeat of earlier measurements, however, with more of the throat thermocouples in proper working order. The bulk of the film temperature and heat flux data was for new test conditions in which either one or both of the propellants were temperature conditioned (cold propellant tests). The test conditions are summarized under Task VIII testing.

II, A, Program Progress (cont.)

4. Task IV - Cooled Chamber Fabrication

During this report period, considerable progress has been made in fabrication of cooled thrust chambers. A total of four cooled chambers, two of each design as discussed in Report NAS 3-14354 Q-2, are being fabricated in the ALRC Research and Advanced Technology Shop.

a. Film Cooled Chamber Fabrication - PN 1160334-1 and -2

Referring to the drawing and schedule, Figures III-10 and III-32 of Program Report Q-2, the status of this hardware is as follows:

Items 2 and 3, Regenerative Cooled Copper Bodies - One unit complete through slotting of coolant channels; second part 50% complete.

Item 1, 304L Jacket (2 units) - All machining and major welding complete, including manifold cover, Item 4. The 304L skirts for both units were rolled, welded, and spun to the contour of the optimized 40:1 Rao nozzle. At the close of the report period, these nozzles had been through a stress relief cycle and were awaiting a final respin operation.

Rolling and welding of conical preforms for the Haynes 188 throats (Item 8) from 0.050-in. sheet material was completed. Welding was accomplished with Haynes 188 weld rod material to provide a maximum strength joint. Spinning of these preforms into the convergent-divergent throat section, although proceeding satisfactorily, has proven more time consuming than had been anticipated. The difficulties are that this material work hardens easily and therefore requires frequent annealing and quenching cycles (five heat treatments per part). The quenching operation produces an extremely tenacious surface oxide, involving the cobalt base and rare earth alloying constituents, which has been found to be resistant to all available pickling and etching solutions. This oxide must therefore be removed mechanically by a hydrohoning operation followed by pickling prior to each spin operation.

II, A, Program Progress (cont.)

At the close of the report period, the throat sections were the critical item, schedulewise, as all operations up to final interface machining and assembly are essentially complete for the first unit. The first throat was completed at the close of the report period, three weeks behind the original schedule. A revised schedule, however, has been prepared, accelerating the assembly operations and the first cooled chamber should be available the last week in March, two weeks before testing is scheduled to start.

b. Fabrication of the Regeneratively Cooled Chambers - PN 1160313

Start of fabrication of the regeneratively cooled chamber body was delayed to facilitate a design change in the aft flange, which eliminated a postassembly welding operation which was marginally close to a brazed joint. As of the close of the report period, fabrication was in process on all major items for the first assembly. The forward and aft flange of the modified design were approximately 75% complete, the film cooled skirt assembly about 50% complete, and the copper body 5% complete. A revised fabrication schedule has been prepared which indicates the first chamber of this design can be delivered mid-April.

5. <u>Task V - Igniter Analysis and Design</u>

No activity.

6. <u>Task VI - Igniter Checkout Testing</u>

No activity.

7. <u>Task VII - Valve Preparation</u>

No activity.

II, A, Program Progress (cont.)

8. Task VIII - Injector Checkout Tests

High P_c APS injector checkout testing was completed during the month of February on the Physics Lab Bay 7 test stand. A total of 90 tests have been completed to date, 15 more than in the original test plan. Of these tests, 81 were heat transfer and performance tests, four were streak chamber tests which were too short in duration (0.5 sec) to obtain accurate performance, four were combustion stability tests, and one was a short pulsing test series. eighteen of these tests, including one streak chamber and the four stability tests, were conducted with cold propellant. Testing with heated propellants, originally planned for this task, has been rescheduled to be investigated in Task IX. Testing during the closing days of January and the month of February is summarized as follows:

Tests 159 to 161 were conducted on a 15 L* copper heat sink chamber with an I-triplet injector at MR = 4, 5 and 6 without film cooling. These tests provided repeat data points of earlier tests at MR = 4 and 5 and new data at a MR of 6. Test durations were 2 sec. The MR = 4 ERE was within 0.5% of earlier data, while the MR = 5 ERE of 97.1 was approximately 1% lower than recorded in earlier tests.

Tests 162 through 166 were conducted using the same injector in the adiabatic wall chamber at 20 L*, a 2.5-in.-long film cooling ring, and 30% film cooling. Test durations ranged from 2 to 10 sec with a nominal core MR from 4.5 to 5.0 and chamber pressures of 300 and 500 psia. These tests provided performance data with film cooling and demonstrated that the adiabatic wall temperature is not a significant function of chamber pressure.

Test 167 was a repeat of earlier tests at MR = 3.0 and 300 psia P_c for performance verification. Results were consistent within about 1.0%. Test 167 was the first test in which significant overpressure (200 psi) was noted in the oxidizer manifold.

II, A, Program Progress (cont.)

Test 168 was a repeat of Test 167 to observe the ignition process. This ignition phenomenon was repeatable. The igniter was disassembled, inspected, and found in proper order. A possible cause for this overpressure is the longer than optimum fuel lead on these tests. Optimum sequencing is simultaneous flow, while actual data show a 0.009-sec fuel lead which, in conjunction with the low MR (3.0), can result in a combustible mixture in the oxidizer manifold.

Tests 169 through 171 were conducted in the thermally reinstrumented 15 L* copper heat sink chamber with a 1-in.-long film cooling ring having a reduced step height. Testing of 2-sec duration was conducted with cold oxidizer at a core MR of 5 and 30 and 20% film cooling at 300 and 500 psia chamber pressure.

Tests 172 through 175 investigated cold oxidizer in a 20 L* copper heat sink chamber with a 2.5-in.-long film cooling ring (30% film cooling) at chamber pressures of 100, 300 and 500 psia.

Tests 176 and 177 tested cold fuel and oxidizer and higher film coolant injection velocities.

Tests 178 through 185 employed the coaxial element injector with an aluminum face plate. This configuration provided swirlers on the oxidizer inlets and a tip recess of 0.080 in. All tests were conducted in the newly instrumented copper heat sink chamber for 2.0-sec duration, except Test 181 which was a 0.5-sec streak chamber test. Tests 178 through 183 were conducted with cold oxidizer and ambient fuel. In Tests 184 and 185, both propellants were cold. Test variables in this series were: L*, percent film cooling, mixture ratio, and chamber pressure. The performance of this configuration was generally lower than all others tested; however, the aluminum face plate gas-side surface thermocouples demonstrated the material feasibility since steady-state face temperatures were 230°F greater than the fuel temperature. With cold fuel, the injector face operates at a temperature less than 100°F.

II, A, Program Progress (cont.)

Tests 186 and 189 were combustion stability tests conducted in a 15 L* copper chamber with SN 2 I-impinging coaxial injector using cold propellants. The results of these tests are discussed in a separate section.

Test 190 involved a brief series of pulse tests to provide system response data for Task X testing.

a. Injector Performance Analysis

The energy release efficiency of the four injector configurations tested to date, including the reduction in efficiency due to the use of up to 30% fuel film cooling, is summarized in Figures II-1 and II-2. Table II-1 provides a tabulation of the test conditions, test hardware, and measured performance for the test data points employed in preparing these figures. The upper part of Figure II-1 provides a data plot of injector efficiency for each design over a range of thrust chamber mixture ratios for various film cooling percentages. The loss in performance due to the diversion of a fixed percentage of the fuel to separate film cooling rings at the injector periphery is treated as a mixture ratio distribution loss which is additive to energy release loss of the core. The lower part of this figure is a cross plot of the data in the respective upper figures at a thrust chamber mixture ratio of 4.0. The upper dashed line at 98% ERE is the maximum reproducible performance for the most efficient injector configuration tested (the I-triplet at 20 L*). The relative ranking of the remaining injector configurations indicates the triplet and showerhead coaxial to be close seconds and the swirler coaxial to be lowest ranking.

The second dashed line at 94.8% ERE indicates the lowest injector energy release plus mixture ratio distribution efficiency which can be employed in conjunction with the selected 40:1 Rao nozzle contour and still maintain the performance goal of 435 sec. The intersection of this line with the

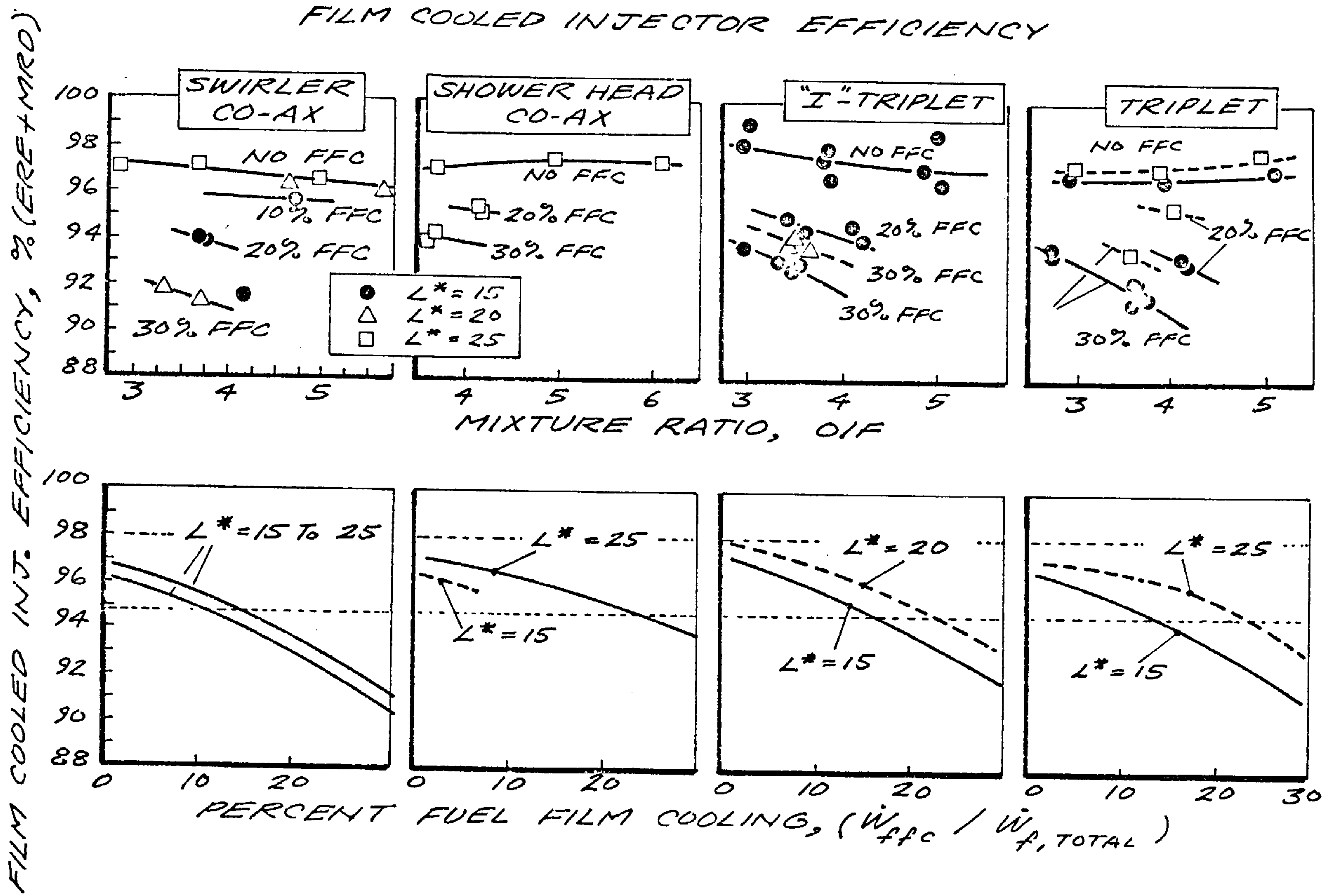

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Figure II-1

INJECTOR ERE (NO FILM COOLING)

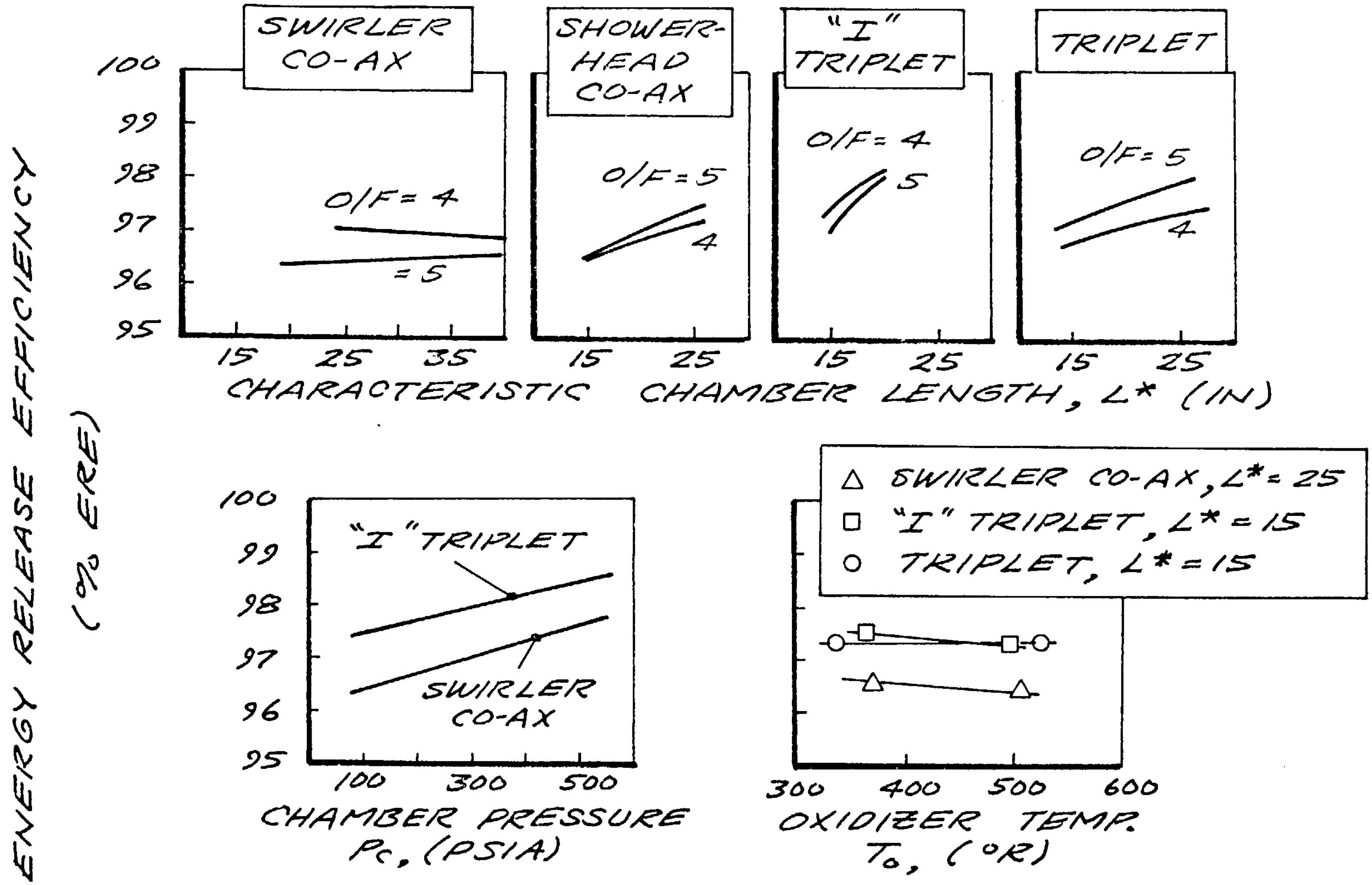


Figure II-2

TABLE II-I

HIGH $\dot{P}_c$ APS - SEA LEVEL PERFORMANCE SUMMARY

Test Series	2K-6												2K-9				
Run No.	101	102	103	104	105	106	108	109	110	111	112	113	102	103	106	107	108
Injector Type	Triplet SN 2								Triplet SN 1				Triplet SN 3				Triplet SN 1
Igniter (lbf, Type)(1)	25-S	''															
L* (Chamber Type)(2), in.	15 (Cu)				25 (Cu)				15 (Cu)							25 (Cu)	15 (Cu)
ϵ	2.91				2.99				2.93				2.87			3.20	2.87
Test Duration, sec	0.5			1.0					0.5	1.5	2.0		1.0				
Data Summary, sec	1.02-1.12	1.02-1.12	1.02-1.12	1.57-1.67	1.57-1.67	1.57-1.67	1.57-1.67	1.57-1.67	1.02-1.12	2.0-2.1	2.6-2.7	2.6-2.7	1.36-1.46	1.26-1.46	1.26-1.46	1.26-1.46	1.26-1.46
P_c, psia	288	294	290	291	292	291	297	289	295	294	297	293	297	306	299	298	310
$\dot{w}_o$, lbm/sec	2.629	2.464	2.835	2.664	2.678	2.623	2.465	2.809	2.618	2.649	2.433	2.848	2.663	2.506	2.960	2.911	2.720
$\dot{w}_f$, lbm/sec	0.651	0.807	0.575	0.661	0.666	0.666	0.819	0.568	0.657	0.660	0.823	0.572	0.683	0.841	0.577	0.577	0.712
$\dot{w}_{fI}$, lbm/sec	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.010	0.010	0.013	0.013	0.013
$(O/F)_{eng}=(O/F)_{core}$	3.95	3.00	4.80	3.94	3.94	3.85	2.95	4.81	3.90	3.93	2.90	4.86	3.84	2.94	5.02	4.94	3.75
$\dot{w}_T$, lbm/sec	3.295	3.286	3.425	3.339	3.359	3.305	3.299	3.392	3.289	3.324	3.271	3.435	3.356	3.357	3.550	3.500	3.445
F_{SL}, lbf	1104.7	1131.2	1118.6	1122.3	1129.7	1116.5	1137.6	1112.3	1105.3	1118.0	1129.1	1114.9	1107.8	1137.8	1153.7	1148.6	1156.7
P_aA_e, lbf	112.4	112.4	112.4	122.4	125.0	125.0	125.0	125.0	122.2	122.2	122.1	122.1	120.5	119.9	119.2	133.3	119.3
F_{vac}, lbf	1227.1	1253.6	1241.0	1244.7	1254.7	1241.5	1262.6	1237.3	1227.5	1240.2	1251.2	1237.0	1228.3	1257.7	1272.9	1281.9	1276.0
$I_{sp,vac}$, sec	372.4	381.5	362.3	372.8	373.6	375.7	382.7	364.8	373.2	373.1	382.5	360.1	366.0	374.6	358.5	366.2	370.4
$I_{sp,theo}$, sec	396.5	401.7	387.5	396.1	397.2	398.0	402.5	388.6	397.3	396.7	401.9	387.2	395.0	399.3	383.3	389.9	395.4
% I_{sp}	93.9	95.0	93.5	94.1	94.1	94.4	95.1	93.9	93.9	94.1	95.2	93.0	92.7	93.8	93.5	93.9	93.7
$\frac{P_c\, g\, A_T}{\dot{w}_T}$, fps	8140	8331	7882	8118	8036	8118	8299	7860	8302	8189	8414	7892	8146	8393	7754	7863	8292
c^*_{theo}, fps	8252	8412	8025	8245	8239	8260	8402	8016	8267	8251	8414	8010	8241	8378	7945	7968	8257
% c*	98.6	99.0	98.2	98.5	97.5	98.3	98.8	98.1	100.4	99.3	100.0	98.5	98.9	100.2	97.6	98.7	100.4
ΔCDL, sec	4.9	5.1	4.6	4.9	4.8	4.8	5.1	4.6	4.9	4.9	5.1	4.6	4.8	5.1	4.6	4.5	4.9
ΔBLL, sec	6.5	6.0	6.5	6.3	6.8	6.7	6.2	7.0	6.3	6.1	5.4	6.2	6.2	5.8	6.3	7.4	6.3
ΔKL, sec	2.0	1.1	2.1	1.9	1.9	1.9	1.1	2.1	1.9	1.9	1.0	2.0	1.8	1.0	1.9	2.1	1.5
ΔI_g FL, sec	1.3	0.7	1.9	1.2	1.2	1.2	0.7	2.0	1.2	1.2	0.7	2.0	0.8	0.5	1.8	1.8	0.9
ΔFFCL, sec	0.0																
ΔERL, sec	9.5	7.2	10.1	8.9	8.8	7.6	6.7	8.2	9.8	9.5	7.2	12.3	15.3	12.4	10.2	7.9	11.4
% (ERE + MRD)	97.3	98.0	96.9	97.4	97.5	97.8	98.1	97.4	97.2	97.3	98.0	96.3	95.9	96.8	96.9	97.5	96.9
% ERE	97.6	98.2	97.4	97.7	97.8	98.1	98.3	97.9	97.5	97.6	98.2	96.8	96.1	96.9	97.3	98.0	97.1
T_{ov}, °R	579	575	572	569	557	562	565	566	575	570	564	563	512	508	525	527	509
T_{fv}, °R	575	571	565	560	547	551	551	554	577	564	560	562	522	521	527	530	517

NOTES: (1) 25 or 50 denotes nominal igniter thrust (lbf)
S: Spark igniter
P: Plasma igniter
C: Catalytic igniter

(2) Cu: Denotes copper heat sink chamber
FFC: Denotes adiabatic film cooled chamber
Abl: Denotes ablative streak chamber

TABLE II-I (cont.)

Test Series	2K-7	→	2K-8														→
Run No.	102	103	102	103	104	105	107	108	109	110	111	112	113	114	115	116	117
Injector Type	"I" Triplet					→	Swirler Coax										→
Igniter (lbf, Type)	25-S																→
L* (Chamber Type), in.	15 (Cu)					→	25 (Cu)								→	40 (Cu)	40 (Cu)
ϵ	2.89	2.89	2.92			→	2.88		→	2.90	2.90	2.91					→
Test Duration, sec	1.0		→	0.5		→	1.0			→	2.0	2.0	0.5		→	1.0	1.0
Data Summary, sec	1.46-1.66	1.46-1.66	1.46-1.66	0.98-1.18	0.98-1.18	0.98-1.18	1.5-1.7	1.5-1.7	1.5-1.7	1.5-1.7	2.4-2.6	2.4-2.6	1.0-1.2	1.0-1.2	1.0-1.2	1.5-1.7	1.5-1.7
P_c, psia	313	309	308	467	460	489	303	308	316	99	102	99	480	468	469	311	318
$\dot{w}_o$, lbm/sec	2.581	3.002	2.698	4.102	4.348	3.920	2.687	2.532	3.079	0.930	0.868	0.993	4.205	3.816	4.410	2.750	3.076
$\dot{w}_f$, lbm/sec	0.845	0.587	0.689	1.051	0.868	1.340	0.716	0.877	0.607	0.228	0.293	0.198	1.133	1.252	0.934	0.742	0.619
$\dot{w}_{fI}$, lbm/sec	0.013	0.013	0.013	0.020	0.020	0.020	0.013	0.013	0.013	0.004	0.004	0.004	0.020	0.020	0.020	0.013	0.013
$(O/F)_{eng}=(O/F)_{core}$	3.01	5.01	3.85	3.83	4.90	2.88	3.68	2.84	4.97	4.01	2.92	4.92	3.65	3.00	4.63	3.64	4.86
$\dot{w}_T$, lbm/sec	3.439	3.602	3.400	5.173	5.236	5.280	3.416	3.422	3.699	1.162	1.165	1.195	5.358	5.088	5.364	3.505	3.708
F_{SL}, lbf	1197.5	1191.3	1151.5	1837.0	1797.6	1918.1	1135.8	1154.3	1195.2	291.9	306.4	299.5	1872.2	1795.3	1834.7	1161.4	1198.0
P_aA_e, lbf	120.3	120.3	120.4	120.7	120.6	120.6	121.2	121.2	121.2	120.7	120.7	120.5	120.4	120.4	120.4	120.4	120.4
F_{vac}, lbf	1317.8	1311.6	1271.9	1957.7	1918.2	2038.7	1257.0	1275.5	1316.4	412.6	427.1	420.0	1992.6	1915.7	1955.1	1281.8	1318.4
$I_{sp,vac}$, sec	383.2	364.1	374.1	378.5	366.4	386.1	368.0	372.8	355.9	355.1	366.5	351.5	371.9	376.5	364.5	365.7	355.6
$I_{sp,theo}$, sec	399.6	383.8	395.7	396.4	386.5	400.6	397.1	400.7	385.2	392.4	399.4	381.8	397.1	399.7	389.2	396.7	385.6
% I_{sp}	95.9	94.9	94.5	95.5	94.8	96.4	92.7	93.0	92.4	90.5	91.8	92.1	93.7	94.2	93.7	92.2	92.2
$\frac{P_c\ g\ A_T}{\dot{w}_T}$, fps	8287	7818	8172	8188	7954	8400	8201	8334	7896	7819	8087	7665	8291	8516	8100	8212	7925
c* theo, fps	8365	7950	8241	8259	8003	8391	8272	8289	7961	8154	8369	7886	8287	8370	8071	8277	7984
% c*	99.1	98.3	99.2	99.1	99.4	100.1	99.1	99.3	99.2	95.9	96.6	97.2	100.0	101.7	100.4	99.2	99.3
$\angle$CDL, sec	5.1	4.6	4.9	5.0	4.6	5.2	4.9	5.1	4.5	4.7	4.9	4.5	4.9	5.1	4.7	4.8	4.5
$\angle$BLL, sec	5.7	6.3	6.2	5.7	5.9	5.3	10.0	9.4	7.7	12.7	12.0	9.8	9.3	9.1	8.4	11.3	9.0
$\angle$KL, sec	1.0	1.7	1.6	1.1	1.3	0.6	1.6	0.8	1.6	5.0	2.5	5.5	1.0	0.7	1.1	1.6	1.8
$\angle I_g$ FL, sec	0.6	1.8	1.0	1.0	1.8	0.6	0.9	0.6	1.7	1.0	0.6	1.7	0.8	0.6	1.5	0.9	1.6
$\angle$FFCL, sec	0.0																→
$\angle$ERL, sec	3.9	5.3	7.9	5.1	6.5	2.9	11.7	12.0	13.7	13.9	12.9	8.8	9.2	7.7	9.0	12.5	13.2
% (ERE + KRD)	98.9	98.2	97.8	98.4	97.9	99.1	96.8	96.9	96.0	96.2	96.6	97.3	97.5	97.9	97.3	96.6	96.2
% ERE	99.0	98.6	98.0	98.7	98.3	99.3	97.1	97.0	96.5	96.5	96.8	97.7	97.7	98.1	97.7	96.8	96.6
T_{ov}, °R	517	516	517	523	526	523	506	508	506	510	510	508	508	510	510	506	503
T_{fv}, °R	525	524	519	526	525	528	520	521	519	515	516	515	517	514	513	N.I.	515

TABLE II-I (cont.)

Test Series	2K-8																
Run No.	118	120	121	122	123	124	125	126	128	129	131	132	133	134	135	136	137
Injector Type	Swirler Coax	SN 3													Showerhead Coax		
Igniter (lbf, Type)	25-S	25-C		25-S											25-C		
L* (Chamber Type), in.	15 (Alb)	25 (Cu)		15 (Cu)					15 (FFC)			25 (Cu)		15 (Abl)	25 (Cu)		
% FFC	0	0	0	30	20	30	30	20	30	30	30	30	20	0			
FFC - Plane, in.	N/A			0	0	2.5								N/A			
ϵ	3.05	2.90	2.90	3.00					3.07			2.93	2.93	3.10	2.93		
Test Duration, sec	0.5	1.0									5.0	1.0	1.0	0.5	1.0	1.0	0.7
Data Summary, sec	1.0-1.2	1.5-1.7	1.5-1.7	1.1-1.3	1.1-1.3	1.1-1.3	1.1-1.3	1.1-1.3	1.0-1.2	1.2-1.4	5.0-5.2	1.3-1.5	1.3-1.5	0.97-1.17	1.4-1.6	1.4-1.6	1.1-1.3
P_c, psia	318	302	310	345	333	337*	335	328	318*	316*	320*	337*	330*	310	313	319	316
$(O/F)_{eng}$	4.81	3.89	2.98	3.62	4.10	3.59	3.76	4.18	3.67	3.64	2.73	3.58	4.00	5.10	3.71	4.95	6.05
$\dot{w}_o$, lbm/sec	3.026	2.715	2.558	3.091	3.073	3.072	3.097	3.089	3.111	3.061	2.803	3.044	3.023	3.073	2.733	3.045	3.240
$\dot{w}_f$, lbm/sec	0.617	0.683	0.842	0.592	0.593	0.592	0.568	0.584	0.586	0.581	0.711	0.587	0.597	0.590	0.720	0.599	0.519
$\dot{w}_{ffc}$, lbm/sec	0	0	0	0.249	0.143	0.252	0.242	0.142	0.249	0.247	0.302	0.250	0.145	0	0	0	0
$\dot{w}_{fI}$, lbm/sec	0.013	0.016	0.016	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.016	0.016	0.016
$\dot{w}_T$, lbm/sec	3.656	3.414	3.416	3.945	3.822	3.928	3.920	3.828	3.959	3.902	3.829	3.893	3.778	3.676	3.469	3.659	3.775
$(O/F)_{core}$	4.81	3.89	2.98	5.11	5.07	5.08	5.33	5.18	5.20	5.15	3.87	5.07	4.96	5.10	3.71	4.95	6.05
F_{SL}, lbf	1217.4	1137.8	1163.1	1290.1	1245.2	1281.0	1271.3	1246.1	1287.0	1275.5	1286.4	1294.4	1262.4	1205.1	1160.8	1191.8	1184.5
P_aA_e, lbf	129.4	120.0	120.0	123.4	123.4	123.6	123.6	123.6	132.2	130.9	130.7	122.2	122.2	131.6	121.9	122.0	122.0
F_{vac}, lbf	1346.8	1257.8	1283.1	1413.5	1368.6	1404.6	1394.9	1369.7	1419.2	1406.4	1417.1	1416.6	1384.6	1336.7	1282.7	1313.8	1306.5
$I_{sp,vac}$, sec	368.4	368.4	375.6	358.3	358.1	357.6	355.9	357.8	358.4	360.4	370.1	363.9	366.5	363.6	369.8	359.0	346.1
$I_{sp,theo}$, sec	388.8	394.9	399.3	398.4	395.1	398.6	397.6	394.4	399.2	399.4	402.8	397.4	394.6	386.0	396.4	384.8	370.9
% I_{sp}	94.8	93.3	94.1	90.0	90.6	89.7	89.5	90.7	89.8	90.2	91.9	91.6	92.9	94.2	93.3	93.3	93.3
$\frac{P_c\, g\, A_T}{\dot{w}_T}$, fps	8172	8137	8348	7868	7847	7732	7691	7724	7549	7619	7866	7897	7971	7839	8220	7936	7636
c* theo, fps	8001	8226	8367	8282	8184	8288	8257	8167	8272	8279	8392	8286	8204	7914	8258	7954	7632
% c*	102.1	98.9	99.8	95.0	95.9	93.3	93.1	94.6	91.3	92.0	93.7	95.3	97.2	99.1	99.5	99.8	100.0
$\angle$ODL, sec	4.6	4.9	5.1	4.7	4.6	4.7	4.6	4.6	4.6	4.7	4.9	4.8	4.8	4.5	4.9	4.5	4.3
$\angle$BLL, sec	4.1	6.9	6.3	3.7	4.8	2.5	2.4	3.2	2.0	2.0	1.9	3.0	4.2	3.5	7.4	7.6	6.1
$\angle$KL, sec	1.9	1.7	1.0	1.3	1.6	1.4	1.5	1.7	1.6	1.5	0.7	1.4	1.6	1.9	1.6	1.8	1.6
$\angle I_g$ FL, sec	1.6	1.2	0.7	0.8	1.0	0.8	0.8	1.1	0.8	0.8	0.5	0.8	1.0	1.8	1.1	2.1	3.0
$\hat{\angle}$FFCL, sec	0.0			19.0	13.5	19.9	21.6	14.5	20.6	19.5	10.7	18.3	10.7	0.0			
$\hat{\angle}$ERL, sec	8.2	11.7	10.5	10.5	11.4	13.4	10.8	11.6	11.2	10.6	14.0	6.3	5.9	10.7	11.6	9.7	9.8
% (ERE + MRD)	97.5	96.7	97.2	92.4	93.4	91.5	91.6	93.1	91.8	92.3	93.8	93.6	95.6	96.8	96.8	96.9	95.6
% ERE	97.9	97.0	97.4	97.4	97.1	96.7	97.3	97.1	97.2	97.3	96.5	98.4	98.5	97.2	97.1	97.5	97.4
T_{ov}, °R	511	501	501	497	498	500	502	503	503	505	499	503	502	503	498	498	501
T_{fv}, °R	512	511	512	507	507	509	510	510	511	512	514	511	511	508	508	507	506

*Based on P_{oJI}

TABLE II-I (cont.)

Test Series	2K-8	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Run No.	138	139	140	141	142	143	145	146	148	149	150	151	152	153	154	157	158
Injector Type	Showerhead Coax	→	→	→	→	→	SN 4	→	SN 3-D	→	"I" Triplet	→	→	→	→	→	→
Igniter (lbf, Type)	25-S	→	→	→	→	→	50-S	→	50-P	→	25-P	→	→	→	→	→	→
L* (Chamber Type), in.	25 (Cu)	→	→	→	15 (Cu)	→	→	→	→	15(FFC)	15 (Cu)	→	→	→	→	15(FFC)	15(Abl)
% FFC	30	20	30	20	0	→	→	→	→	30	0	→	→	→	→	30	0
FFC - Plane, in.	0	0	2.5	2.5	N/A	→	→	→	→	2.5	N/A	→	→	→	→	2.5	N/A
ϵ	2.93	→	→	→	2.92	2.92	2.94	2.94	2.96	3.00	2.97	→	→	→	→	3.00	3.10
Test Duration, sec	1.0	→	→	→	→	→	→	→	→	→	→	→	→	→	→	5.0	0.5
Data Summary, sec	1.35-1.55	1.35-1.55	1.35-1.55	1.35-1.55	1.35-1.55	1.35-1.55	1.35-1.55	1.35-1.55	1.1-1.5	1.3-1.5	1.35-1.55	1.35-1.55	1.35-1.55	1.35-1.55	1.35-1.55	5.5-5.7	0.92-1.02
P_c, psia	346*	338*	344*	337*	311	311	300	293	314	315*	309	317	104	106	101	321*	312
$(O/F)_{eng}$	3.67	4.14	3.59	4.17	3.88	6.21	4.30	5.37	3.93	2.75	3.87	5.05	3.90	5.07	6.05	3.47	4.93
$\dot{w}_o$, lbm/sec	3.062	3.067	3.036	3.058	2.736	3.235	2.712	2.897	2.791	2.747	2.729	3.049	0.932	1.033	1.054	3.049	2.934
$\dot{w}_f$, lbm/sec	0.577	0.585	0.584	0.580	0.692	0.508	0.608	0.517	0.687	0.685	0.694	0.592	0.228	0.193	0.163	0.608	0.584
$\dot{w}_{ffc}$, lbm/sec	0.246	0.142	0.248	0.141	0.0	→	→	→	→	0.292	0.0	→	→	→	→	0.259	0.0
$\dot{w}_{fI}$, lbm/sec	0.013	0.013	0.013	0.013	0.013	0.013	0.022	0.022	0.023	0.023	0.011	0.011	0.011	0.011	0.011	0.011	0.011
$\dot{w}_T$, lbm/sec	3.898	3.807	3.881	3.792	3.441	3.756	3.343	3.436	3.501	3.746	3.434	3.652	1.171	1.236	1.228	3.926	3.529
$(O/F)_{core}$	5.19	5.13	5.08	5.16	3.88	6.21	4.30	5.37	3.93	3.88	3.87	5.05	3.90	5.07	6.05	4.93	4.93
F_{SL}, lbf	1291.8	1259.1	1289.2	1256.9	1145.2	1158.0	1110.9	1083.4	1168.6	1251.0	1148.2	1183.9	306.9	312.9	294.3	1291.9	1194.7
P_aA_e, lbf	120.0	120.0	119.8	119.8	118.9	118.9	120.3	120.3	121.6	128.3	120.8	120.7	120.7	→	→	129.4	132.2
F_{vac}, lbf	1411.8	1379.1	1409.0	1376.7	1264.1	1276.9	1231.2	1203.7	1290.2	1379.3	1269.0	1304.6	427.6	433.6	415.0	1421.3	1326.9
$I_{sp,vac}$, sec	362.3	362.3	363.0	363.0	367.4	340.0	368.3	350.3	368.6	368.2	369.5	357.3	365.2	350.7	338.0	362.0	376.0
$I_{sp,theo}$, sec	396.8	393.4	397.1	393.2	395.2	368.6	388.0	376.6	395.8	401.7	396.2	384.5	394.5	380.9	367.3	399.3	388.6
% I_{sp}	91.3	92.1	91.4	92.3	93.0	92.2	94.9	93.0	93.1	91.7	93.3	92.9	92.6	92.1	92.0	90.7	96.7
$\frac{P_c\, g\, A_T}{\dot{w}_T}$, fps	8044	8047	8043	8062	8138	7471	8069	7666	8061	7908	8034	7734	7965	7651	7349	7879	8230
c* theo, fps	8268	8169	8282	8165	8223	7584	8047	7770	8224	8389	8230	7931	8182	7845	7538	8307	7974
% c*	97.3	98.5	97.1	98.7	99.0	98.5	100.3	98.7	98.0	94.3	97.6	97.5	97.4	97.5	97.5	94.9	103.2
$\angle$CDL, sec	4.8	4.7	4.8	4.7	4.8	4.2	4.8	4.4	4.8	4.9	4.8	4.5	4.8	4.4	4.2	4.7	4.6
ΔBLL, sec	5.4	6.5	3.6	4.8	6.8	5.2	6.5	6.1	6.3	1.9	6.1	6.1	7.9	7.8	6.7	2.0	3.4
$\angle$KL, sec	1.4	1.6	1.3	1.6	1.7	1.7	1.9	2.0	1.6	0.7	1.6	1.6	4.8	5.4	5.4	1.3	1.8
$\angle I_g$ FL, sec	0.8	1.1	0.8	1.1	1.0	2.6	2.2	3.7	1.8	2.8	0.9	1.5	2.7	4.5	6.5	0.6	1.5
ΔFFCL, sec	12.1	7.4	13.5	8.1	0.0	→	→	→	→	10.4	0.0	→	→	→	→	17.8	0.0
$\angle$ERL, sec	10.0	9.9	10.0	9.9	13.6	14.9	4.3	10.1	12.8	12.9	13.3	13.5	9.1	8.1	6.5	10.9	1.3
% (ERE + MRD)	94.2	95.3	93.9	95.1	96.3	95.3	98.3	96.3	96.3	92.5	96.4	96.1	97.0	96.7	96.5	92.7	99.3
% ERE	97.5	97.5	97.5	97.5	96.6	96.0	98.9	97.3	96.8	96.8	96.6	96.5	97.7	97.9	98.2	97.3	99.7
T_{ov}, °R	496	497	498	499	498	498	329	334	505	510	507	509	511	511	509	512	528
T_{iv}, °R	505	506	507	507	507	507	344	344	512	514	513	513	515	515	514	514	528

*Based on P_{oJI}

Table II-I (cont.)

Test Series	2K-8	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Run No.	159	160	161	163	166	167	169	170	171	172	173	174	175	176	177	178	179
Injector Type	"I" Triplet	→	→	→	→	→	→	→	→	→	→	→	→	→	→	Recessed	Swirl C
Igniter (lbf, Type)	25-S	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
L* (Chamber Type), in.	15 (Cu)	→	→	20(FFC)	→	15 (Cu)	→	→	→	20 (Cu)	15 (Cu)	→	→	→	→	→	→
% FFC	0	→	→	30	30	0	30	20	30	→	→	→	→	20	20	30	20
FFC - Plane, in.	N/A	→	→	2.5	2.5	N/A	1.0	→	→	2.5	→	→	→	1.0	1.0	0	0
ϵ	2.95	→	→	3.03	3.03	2.96	2.92	2.92	2.94	→	→	→	→	2.93	→	→	→
Test Duration, sec	2.0	→	→	10.0	1.0	2.0	→	→	→	→	→	→	→	→	→	→	→
Data Summary, sec	2.3-2.5	2.3-2.5	2.3-2.5	10.3-10.5	1.2-1.4	2.5-2.7	2.2-2.4	2.2-2.4	2.2-2.4	2.2-2.4	2.2-2.4	2.2-2.4	2.2-2.4	2.2-2.4	2.2-2.4	2.2-2.4	2.2-2.4
P_c, psia	310	314	313	331*	473*	318	298	295	467	488	301	297	99	288	284	310	298
$(O/F)_{eng}$	3.82	4.87	5.89	3.45	3.52	2.96	2.97	3.42	3.34	3.63	3.34	3.55	3.47	3.59	4.22	4.16	3.68
$\dot{w}_o$, lbm/sec	2.719	2.984	3.178	3.152	4.516	2.566	2.612	2.668	4.255	4.554	2.767	2.786	0.938	2.675	2.771	3.040	2.761
$\dot{w}_f$, lbm/sec	0.701	0.602	0.528	0.633	0.888	0.855	0.610	0.619	0.882	0.867	0.574	0.544	0.187	0.595	0.521	0.506	0.595
$\dot{w}_{ffc}$, lbm/sec	0.0	→	→	0.268	0.377	0.0	0.259	0.150	0.376	0.368	0.243	0.230	0.080	0.140	0.124	0.214	0.143
$\dot{w}_{fI}$, lbm/sec	0.011	0.011	0.011	0.011	0.019	0.011	0.011	0.011	0.018	0.018	0.011	0.011	0.004	0.011	0.011	0.012	0.011
$\dot{w}_T$, lbm/sec	3.431	3.597	3.717	4.064	5.800	3.432	3.492	3.448	5.531	5.807	3.595	3.571	1.209	3.421	3.427	3.772	3.510
$(O/F)_{core}$	3.82	4.87	5.89	4.89	4.98	2.96	4.21	4.24	4.72	5.14	4.73	5.02	4.91	4.42	5.21	5.88	4.55
F_{SL}, lbf	1158.7	1176.8	1171.5	1360.2	2007.0	1186.4	1150.3	1143.7	1880.1	1985.0	1177.3	1162.8	310.9	1103.9	1094.8	1189.3	1139.3
P_aA_e, lbf	121.3	121.3	121.3	130.4	130.4	121.4	124.8	124.8	125.1	125.1	125.0	→	→	124.0	124.0	125.5	125.5
F_{vac}, lbf	1280.0	1298.1	1292.8	1490.6	2137.4	1307.8	1275.1	1268.5	2005.2	2110.1	1302.3	1287.8	435.9	1227.9	1218.8	1314.8	1264.8
$I_{sp,vac}$, sec	373.0	360.9	347.8	366.7	368.5	381.0	365.2	367.9	362.5	363.4	362.3	360.7	360.5	358.9	355.6	348.6	360.3
$I_{sp,theo}$, sec	396.0	386.1	373.3	399.7	399.3	400.4	399.2	397.5	398.0	396.9	398.2	397.2	396.7	390.5	388.7	392.2	395.3
% I_{sp}	94.2	93.5	93.2	91.8	92.3	95.1	91.5	92.6	91.1	91.6	91.0	90.8	90.9	91.9	91.5	88.9	91.1
$\frac{P_c\ g\ A_T}{\dot{w}_T}$, fps	8105	7830	7543	7654	7650	8288	7985	7998	7906	7870	7856	7802	7673	7885	7755	7689	7925
c* theo, fps	8236	7978	7680	8307	8300	8369	8355	8299	8309	8271	8311	8279	8266	8139	8059	8139	8237
% c*	98.4	98.2	98.2	92.1	92.2	99.0	95.6	96.4	95.1	95.2	94.5	94.2	92.8	96.9	96.2	94.5	96.2
ΔCDL, sec	4.9	4.6	4.3	4.8	4.8	5.1	4.9	4.9	4.8	→	→	→	→	4.7	4.6	→	→
ΔBLL, sec	5.8	6.1	5.4	2.1	2.0	5.5	3.2	4.2	2.9	2.5	→	→	3.1	3.6	3.5	3.7	4.8
ΔKL, sec	1.7	1.8	1.7	1.3	1.0	1.0	1.1	1.5	0.9	1.0	1.4	1.6	4.2	1.7	2.0	1.8	1.7
ΔI_g FL, sec	0.9	1.4	2.0	0.6	0.7	0.5	0.5	0.7	0.7	0.7	0.6	0.7	0.7	0.8	1.1	1.0	0.8
ΔFFCL, sec	0.0	0.0	0.0	17.9	17.6	0.0	13.0	9.6	17.6	17.9	16.8	18.8	21.3	10.1	13.5	23.7	10.9
ΔERL, sec	9.7	11.3	12.2	6.3	4.7	7.4	11.3	8.7	8.6	6.6	9.8	8.1	2.1	10.7	8.4	8.8	12.2
% (ERE + MRD)	97.3	96.7	96.2	93.8	94.2	98.0	93.8	95.0	93.3	93.7	93.2	93.1	93.9	94.5	94.1	91.4	93.9
% ERE	97.5	97.1	96.7	98.4	98.8	98.2	97.2	97.8	97.8	98.3	97.5	98.0	99.5	97.3	97.8	97.7	96.9
T_{ov}, °R	492	499	507	500	491	499	356	371	341	326	358	365	359	347	303	316	352
T_{fv}, °R	505	506	508	513	506	513	519	519	513	522	523	522	523	289	353	491	494

*Based on P_{oJI}

TABLE II-1 (cont.)

Test Series	2K-8	→	→	→	→	→	→
Run No.	180	181	182	183	184	185	186
Injector Type	Recessed	Swirl Coax	→	→	→	→	I-Triplet
Igniter (lbf, Type)	25-S	→	→	→	→	→	
L* (Chamber Type), in.	15 (Cu)	15(Abl)	20 (Cu)	→	→	→	15 (Cu)
% FFC	20	10	0	0	30	30	20
FFC - Plane, in.	0	0	N/A	N/A	2.5	2.5	0
ϵ	2.93	3.09	2.93	→	→	→	→
Test Duration, sec	2.0	0.5	2.0	→	→	→	1.0
Data Summary, sec	2.2-2.4	0.8-1.0	2.2-2.4	2.2-2.4	1.4-1.5	2.2-2.4	1.2-1.4
P_c, psia	449	333	284	278	307	300	314
$(O/F)_{eng}$	3.75	4.72	4.65	5.65	3.31	3.71	4.09
$\dot{w}_o$, lbm/sec	4.169	3.212	2.789	2.926	2.821	2.860	3.018
$\dot{w}_f$, lbm/sec	0.880	0.606	0.589	0.506	0.593	0.534	0.587
$\dot{w}_{ffc}$, lbm/sec	0.214	0.064	0	0	0.249	0.226	0.140
$\dot{w}_{fI}$, lbm/sec	0.018	0.011	→	→	→	→	→
$\dot{w}_T$, lbm/sec	5.281	3.893	3.389	3.443	3.674	3.631	3.756
$(O/F)_{core}$	4.64	5.20	4.65	5.65	4.67	5.24	5.05
F_{SL}, lbf	1781.8	1281.6	1089.5	1069.8	1170.4	1145.7	1222.1
$P_a A_e$, lbf	125.5	131.7	125.3	→	→	→	125.2
F_{vac}, lbf	1907.3	1413.3	1214.8	1195.1	1295.7	1271.0	1347.3
$I_{sp,vac}$, sec	361.2	363.0	358.5	347.1	352.6	350.1	358.7
$I_{sp,theo}$, sec	395.6	390.1	387.6	375.0	393.8	393.5	390.7
% I_{sp}	91.3	93.1	92.5	92.6	89.5	89.0	91.8
$\frac{P_c\ g\ A_T}{W_T}$, fps	7948	7958	7837	7551	7807	7723	7837
c^*_{theo}, fps	8239	8011	8022	7726	8205	8189	8107
% c*	96.5	99.3	97.7	97.7	95.1	94.3	96.7
ΔCDL, sec	4.5	4.5	4.5	4.5	4.7	4.6	4.7
ΔBLL, sec	4.4	3.6	8.0	6.5	2.7	2.7	4.8
ΔKL, sec	1.1	1.8	2.0	2.0	1.4	1.7	1.7
ΔI_g FL, sec	0.9	1.3	1.4	2.1	0.6	0.8	0.9
ΔFFCL, sec	10.1	7.1	0	0	16.2	19.9	12.9
ΔERL, sec	13.4	8.8	13.2	12.8	15.6	13.7	7.0
% (ERE + MRD)	93.8	95.6	96.2	96.0	91.8	91.3	94.7
% ERE	96.6	97.7	96.6	96.6	96.0	96.5	98.2
T_{ov}, °R	370	342	369	370	371	389	379
T_{fv}, °R	492	503	508	506	341	399	376

*Based on P_{oJI}

II, A, Program Progress (cont.)

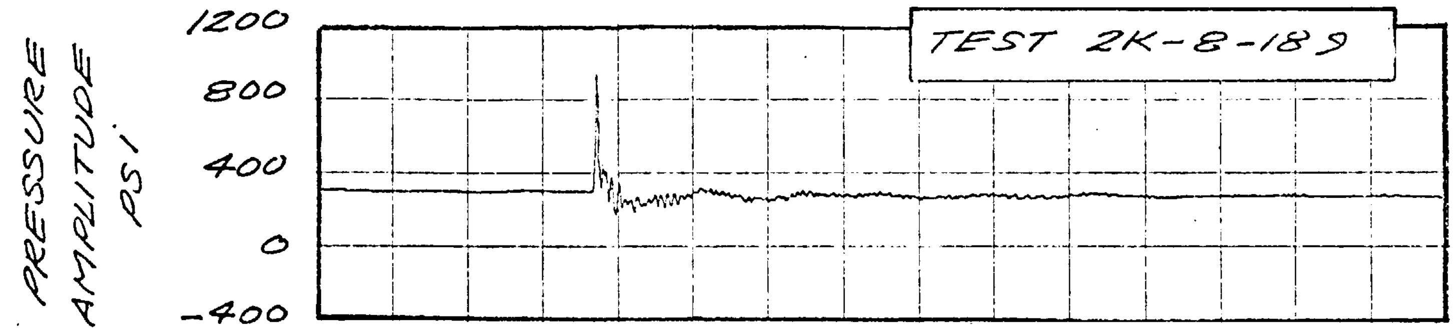
experimental performance line for each injector at the respective L* values determines the maximum amount of fuel which can be employed as fuel film coolant for extending chamber life at a nominal thrust chamber mixture ratio of 4.0. Longer L* values allow additional film cooling to be employed. The swirler coaxial design allows the least amount of film cooling (approximately 12%), while the maximum amounts range between 22 and 25% for the other injectors, depending on L*.

Figure II-2 shows: (1) the influence of characteristic chamber length (L*) for each design at mixture ratios of 4 and 5, (2) the effect of chamber pressure at mixture ratio of 4.0, and (3) the influence of oxidizer temperature on the 0% film cooling energy release efficiency.

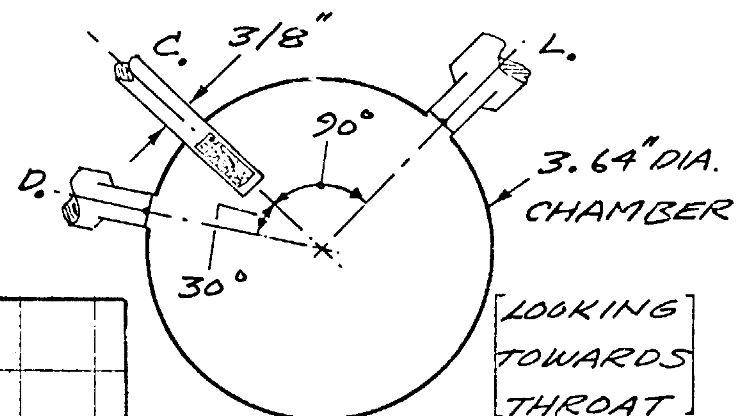
b. Stability Testing

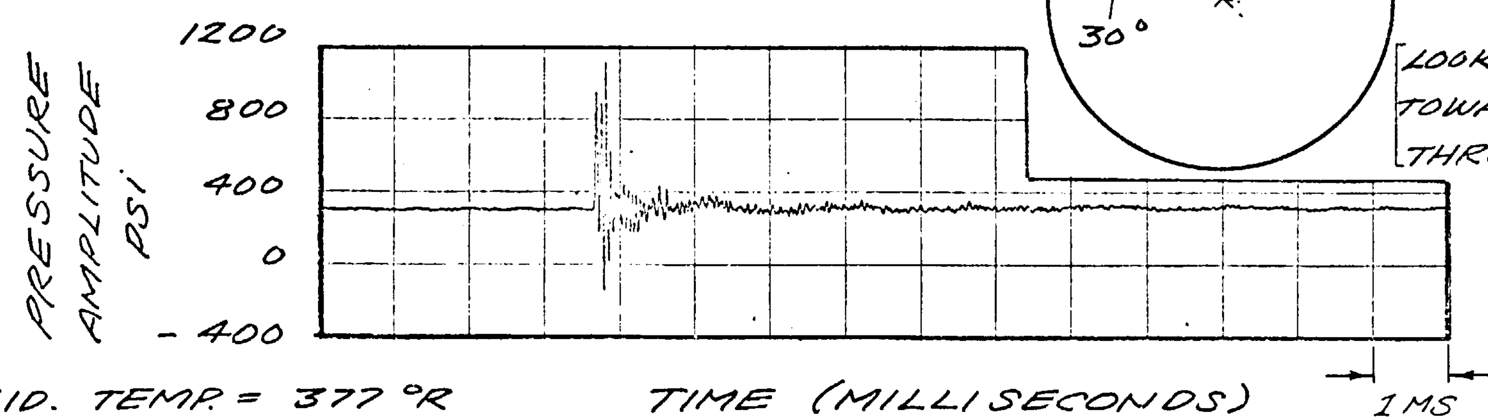
Stability Tests 2K-8-187, -188, and -189 were conducted in a 15 L* copper heat sink chamber instrumented with two flush-mounted Photocon 307 transducers located 120 degrees apart and 1-in. downstream of the injector as shown schematically in Figure II-3. All tests were conducted with SN 2 (I pattern) impinging coaxial element injector using cold propellants. The test conditions are summarized in Table II-2. The combustion dynamic stability was evaluated by perturbating the chamber pressure with a thermally detonated 2-grain Teflon-encased RDX charge. The results of one of these stability tests is displayed in Figures II-3 and II-4. Prior to bomb detonation, peak-to-peak pressure amplitude oscillations are approximately 5% of chamber pressure, otherwise stated as 300 psia $\pm$ 7.5 psi. The bomb detonation resulted in a nominal 200% overpressure as recorded by the Photocon pressure transducers. From Figure II-3, in which each major time division represents 0.001 sec, it can be seen that the pressure oscillation decay to within a few percent of the pre-excited state in 0.006 sec. Figure II-4 shows the results of a spectral density analysis of the chamber pressure oscillations at all frequencies. Also shown are the predicted frequencies at which some resonance could be expected.

COMBUSTION STABILITY BOMB TEST RESULTS



C. 2.0 GRAIN RDX BOMB
D. 307 PHOTOCON, 2000 PSI DC RANGE
L. 307 PHOTOCON, 1000 PSI DC RANGE





OXID. TEMP. = 377 °R
FUEL TEMP. = 384 °R

TIME (MILLISECONDS)

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AGCS 0100-71 (REV 5/70)

Figure II-3

SPECTRAL ANALYSIS OF BOMB TEST DATA

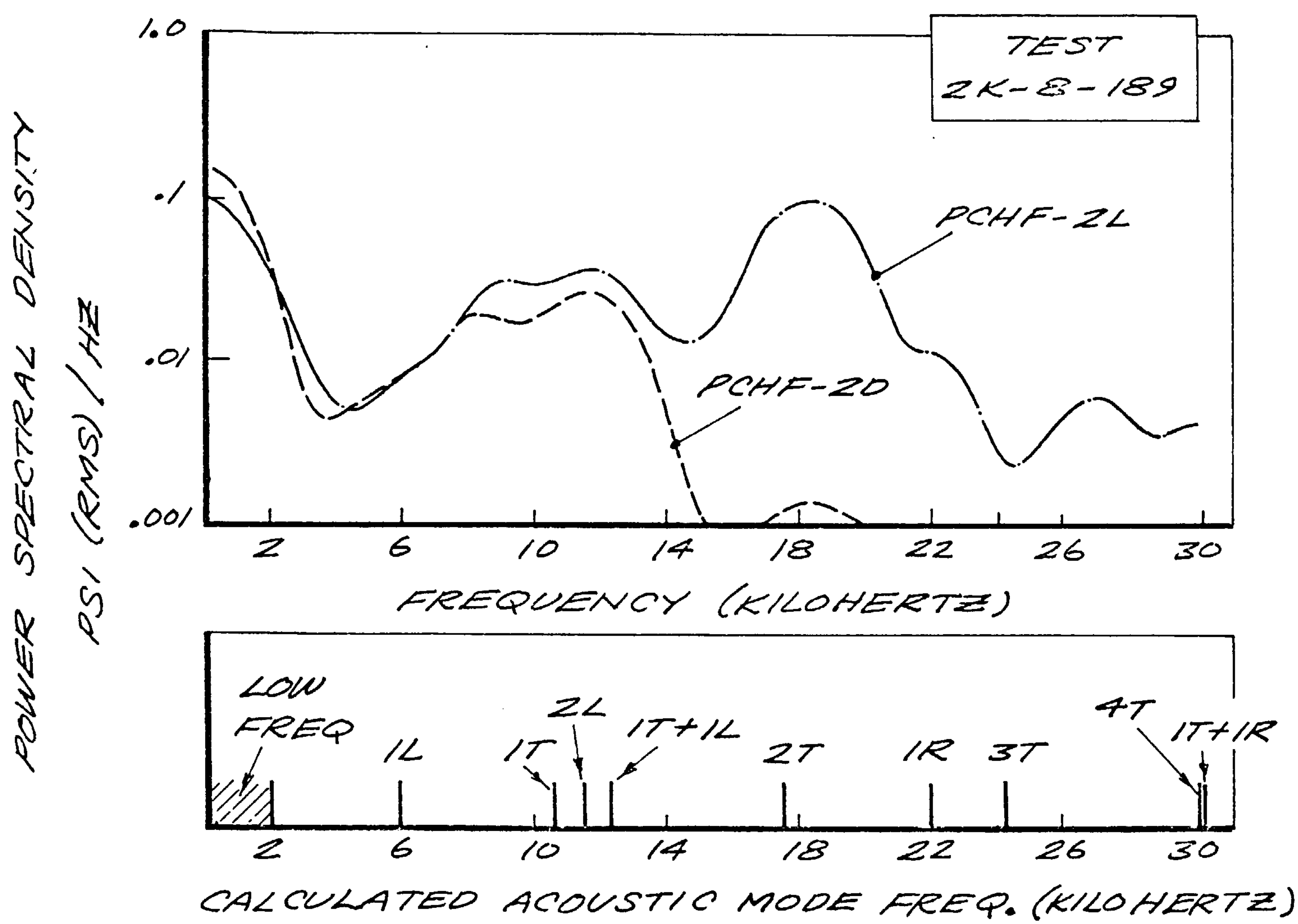

Figure II-4

TABLE II-2

SUMMARY OF STABILITY TESTING

Test No.	Propellant Temp, °R Oxidizer	Fuel	P_c 2K*	P_c 1K
2K-8-187	408	400	680/680	580/670
2K-8-188	360	390	230/370	510/240
2K-8-189	377	384	720/720	650/810

*Initial ΔP/maximum ΔP, psia

II, A, Program Progress (cont.)

9. Task IX - Cooled Chamber Testing

As a result of the stop work order on Low P_c chamber testing and redirection of the program to provide an expanded High P_c test program with cold propellants, it is now planned to conduct all High P_c testing in altitude cell J-3 rather than J-4. Test Stand J-3, currently being employed in Low P_c testing, now contains propellant flow control valves, tube type heat exchanger for propellant condition, and the potential for more cost effective altitude testing.

A preliminary plan for testing the 40:1 area ratio cooled thrust chambers in Test Stand J-3 was prepared for presentation at a 2 March program review with the NASA program manager. This test plan was based on transient thermal analyses conducted during the last report period to determine the fire durations required to approach thermal steady state of the film cooled nozzle at 40:1 area ratio (the slowest responding location). This analysis provided the following estimated times:

% of Steady-State Temperature	Seconds
95	70
98	140

Because of the long skirt warmup times, the recommended test plan includes evaluating several film cooling flow rates and thrust chamber mixture ratios during a single long burn.

Task IX testing is now scheduled to begin in mid-April.

10. Task X - Pulse Testing

Durability of the new Brute III DC power supply which provides a single power source for the two igniter valves and two thrust chamber valves. The spark igniter and thrust chamber valves discussed* in Tasks VI and VII

*Quarterly Report No. 2

II, A, Program Progress (cont.)

have been successfully demonstrated in a series of 2500 thruster hot pulses. The test duty cycle consisted of 0.050-sec on times and 0.150-sec off times in a film cooled 3:1 expansion ratio chamber. The system functioned flawlessly except for minor propellant leakage through the valve stems.

A flow system schematic and test plan for obtaining bit impulse and bit specific impulse with 40:1 cooled chambers has been formulated for presentation at the 2 March program review with the NASA program manager. Accurate measurement of the propellant temperatures and flow rates in pulsing is anticipated to be the most difficult aspect of this task.

B. CURRENT PROBLEMS

No significant technical problems have been encountered during this report period. Funding on the various technical tasks, however, deviates from the originally planned values. The higher-than-planned expenditures in Task VIII testing, for example, represent expanded scope, which was made possible by the savings which have been achieved in other areas, such as injector and chamber fabrication.

C. WORK TO BE PERFORMED IN NEXT REPORT PERIOD

Task I - Injector Analysis and Design - No activity.

Task II - Injector Fabrication

Modify selected injectors for use in cooled chamber testing.

Task III - Cooled Chamber Analysis and Design

Continue to evaluate results of Task VIII heat transfer tests and determine impact on selected designs.

II, C, Work to be Performed in Next Report Period (cont.)

Task IV - Cooled Chamber Fabrication

Continue fabrication of four cooled thrust chambers--two units of each concept. First unit should be available during the next report period.

Tasks V through VII - No activity.

Task VIII - Injector Checkout Tests

Complete documentation of test activities in this task.

Task IX - Cooled Chamber Tests

Finalize cooled chamber test plan for the J-3 altitude test facilities and propellant requirements for longer duration tests. Prepare J-3 test facility for a mid-April start date for testing. Checkout new propellant heat exchangers to determine minimum temperature vs flow rate. Move two 16 ft^3 insulated propellant tanks alongside J-3 test facility. These tanks will provide a portion of the P,V,T - mass balance storage system that will be employed in propellant flow measurement.

Task X - Pulse Tests - No activity.

III. LOW PRESSURE TECHNOLOGY PROGRAM

A. PROGRAM PROGRESS (TASKS XI THROUGH XX)

During this reporting period, a contract stop work order was received from the NASA/LeRC contracting officer, directing that all work relative to the following areas be stopped:

- Analysis, design, fabrication, and testing of the low pressure vaned injector.
- Valve preparation for low P_c.
- Low pressure cooled thrust chamber analysis, design, fabrication, and testing.

Verbal communication with the NASA/LeRC program manager resulted in definition of a reduced scope testing program for the coaxial element injector. Four additional test series were conducted, concluding this task with a total of 34 tests: ten ignition, facility verification, and control sequence tests and 24 tests for performance and thermal data.

1. Task XI - Injector Analysis and Design

The activities on this task were stopped during this report period.

A review of the vaned injector hydrogen orifice pattern had been initiated to improve the mixture ratio distribution along the vane. Flow testing indicated that the hydrogen orifice pattern was causing a nonuniform flow of oxygen in the area of transition from a double row to a single row of orifices. Undesirable O/F ratios were expected and a correction was considered necessary. This activity was stopped before it was completed.

2. Task XII - Injector Fabrication

Fabrication of the vaned injector was stopped during this reporting period.

III, A, Program Progress (Tasks XI Through XX) (cont.)

3. Task XIII - Thrust Chamber Analysis and Design

This activity was completed earlier and was awaiting hot fire test results and a fabrication evaluation. All effort on this task has been stopped.

4. Task XIV - Thrust Chamber Fabrication

Fabrication of thermal instrumentation and application of the ablative material for streak chamber testing was completed during this period. Activities related to the fabrication of cooled chambers were stopped.

5. Task XV - Catalytic Igniter Analysis and Design

This task has been completed.

6. Task XVI - Catalytic Igniter Fabrication and Test

Twenty catalytic igniter tests were conducted during this report period. These tests, conducted at simulated altitude conditions with ambient temperaturepropellants, included surveys of the effect of mixture ratio and weight flow on response characteristics. Posttest inspection of the hardware showed some damage to the igniter injector face plate caused by a slow closing oxygen valve. The damage was limited to the final distribution plate which will be removed prior to the next test series. With this plate removed, the propellants will be injected somewhat more coarsely than before.

Table III-1 summarizes the results of these tests. Ignition delay is defined as the time between the start of oxygen manifold pressure buildup (the lagging propellant) and the involvement of the secondary oxygen with the reaction products from the catalyst bed. When the secondary oxygen

TABLE III-1

TASK XVI CATALYTIC IGNITER TEST SUMMARY

Test IG-2C	Duration, sec	$\dot{w}_f$, lb/sec	$\dot{w}_o$, lb/sec	Sec. O_2 Reaction Time, sec	Remarks
-101	0.2	0.0125	0.0625	--	
-102	0.2	0.0125	0.0625	--	
-103	1.0	0.0125	0.0625	--	
-104	5.0	0.0125	0.0625	--	
-105	5.0	0.0167	0.0835	0.855	Posttest modifications to introduce part of secondary O_2 nearer catalyst bed
-106	2.0	0.0167	0.0835	--	
-107	2.0	0.0167	0.0835	--	
-108	2.0	0.0125	0.125	1.64	
-109	2.0	0.0125	0.156	0.085	Posttest modification to return secondary O_2 injection to original configuration. Installed 0.093 dia balance orifice in primary O_2 passage.
-110	0.3	0.0125	0.0625	--	
-111	0.3	0.0125	0.0625	--	
-112	2.0	0.0125	0.0625	--	
-113	2.0	0.0187	0.093	--	
-114	2.0	0.0187	0.093	0.74	
-115	2.0	0.0187	0.093	0.25	
-116	2.0	0.0187	0.093	0.68	
-117	2.0	0.0125	0.093	0.59	
-118	2.0	0.0125	0.11	0.12	
-119	2.0	0.0156	0.11	0.39	
-120	2.0	0.0156	0.11	0.03	Hot restart

III, A, Program Progress (Tasks XI Through XX) (cont.)

begins to react with the products from the catalyst bed, an increase in pressure is clearly evident. A photo cell located in the environmental simulation chamber also simultaneously reflects the initiation of this reaction.

Three parameters were varied during these tests. Pretest catalyst bed temperature ranged from 35 to 365°F, total weight flow ranged from 0.075 to 0.168 lb/sec, and overall igniter O/F was varied from 5 to 12.5. As expected, increasing the level of any of the above parameters tended to reduce the time required for secondary O_2 reaction. The shortest reaction time was observed during a hot restart test when the secondary oxygen reacted 30 ms from the start of oxygen manifold pressure buildup. With ambient temperature hardware, the fastest reaction time observed was 85 ms. This occurred during a test at the highest O/F and with two times the design weight flow.

The catalyst bed temperature levels, which were reached near the end of the test periods, were somewhat lower than expected, indicating that the catalyst bed mixture ratio was somewhat lower than designed. To further evaluate this condition, a series of tests have been scheduled to examine operation of the catalyst bed alone, after which the secondary oxygen flow will be reintroduced.

7. Task XVII - Propellant Valves Preparation

Completion of this task has been awaiting the installation of heat exchangers for hot and cold propellant tests. This activity has been stopped and no further effort is anticipated.

8. Task XVIII - Injector Testing

a. Status

The contract stop work order clearly stops all effort related to the vaned injector testing. In conversation with the NASA/LeRC project manager, the scope of the coaxial injector testing was reduced to conclude

III, A, Program Progress (Tasks XI Through XX) (cont.)

with four test series for performance and thermal data. Upon completion of these tests, no further testing is planned and the effort on this task will be limited to the reduction, analysis, and documentation of the test results. The final four test series have been conducted and no additional hot fire tests are scheduled.

b. Test Summary

Thirty-four tests were conducted during this period. Ten tests were engine hardware and facility verification firings to check out igniter operation and to evaluate operation of the facility protection devices. (Considerable care was taken to preclude introduction of a significant quantity of hydrogen into the facility.) Table III-2 summarizes the data for the 24 engine tests.

The initial sequence of Tests 1680-D02-OA-001 through -022 were conducted in the J-3 altitude simulation facility using the J-3 steam ejector system. For the final test series (-023 through -034), the J-4 steam ejector system was used to provide more capacity to expel the low molecular weight exhaust products, increasing the allowable test duration.

Tests were conducted using the SN 001 coaxial element injector. Chamber L*'s of 16 and 26 in. were evaluated. Three film coolant injection sleeves were tested to evaluate the effect of coolant injection velocity and injection location. A streak chamber was prepared and tested.

The first series of tests were conducted for a nominal duration of 5 sec using a 26 L* chamber and a 20% film coolant ring (designed for a coolant-to-gas velocity ratio of 1) 2.78 in. long. The matrix for these tests was planned to evaluate coolant quantity (30, 20, and 10%) at a fixed engine O/F of 2.5, followed by an evaluation of engine O/F (4 to 2) with the nominal 20% coolant flow.

TABLE III-2

LOW P_c O_2/H_2 APS ENGINE TEST SUMMARY

Test 1680-D02-OA	Dur, sec	Data Time, sec	Injector	Chamber	L^*/L', in.	P_c, psia	$MR_{O/A}$	MR_J	% FFC	P_A, psia	$\dot{w}_{oJ}$, lb/sec	$\dot{w}_{fJ}$, lb/sec	$\dot{w}_{fc}$, lb/sec	$\dot{w}_T$,* lb/sec	% $\dot{w}_I$	I_{spv}, lbf-sec/lbm	F_{vac}, lbf	c*, ft/sec
-001	0.3	N/A	200 Ele Coax SN 001	Film Cooled SN 1 20% 2.78" Ring	26/12	Sea Level Ignition Check												
-002	0.3	N/A				Altitude Ignition Check												
-003	1.04	0.5-1.0				15.1	2.55	3.69	30.0	0.137	2.90	0.79	0.34	4.04	0.27	376.0	1519.3	7929
-004	2.59	2.2-2.35				15.3	2.62	3.71	28.5	0.565	2.99	0.80	0.33	4.13	0.25	377.8	1559.5	7871
-005	--	--				Facility Safety Sequence Test												
-006	--	--				Facility Safety Sequence Test												
-007	--	--				Facility Safety Sequence Test												
-008	--	--				Facility Safety Sequence Test												
-009	--	--				Facility Safety Sequence Test												
-010	2.59	1.0-2.5				15.5	2.53	3.26	21.4	0.345	2.95	0.91	0.25	4.12	0.27	384.1	1581.5	7963
-011	--	--				Facility Safety Sequence Test												
-012	5.07	1.0-2.9				15.2	2.48	2.80	11.2	0.385	2.85	1.02	0.13	4.01	0.27	386.0	1539.1	8056
-013	5.08	1.0-2.9				14.4	2.28	2.99	22.7	0.386	2.65	0.89	0.26	3.81	0.28	381.6	1448.5	7991
-014	5.09	1.0-4.5				15.9	3.93	5.07	21.3	0.421	3.54	0.70	0.19	4.44	0.24	366.8	1624.8	7586
-015	5.09	1.0-1.8				15.2	1.97	2.48	19.9	0.523	2.64	1.06	0.26	3.98	0.27	374.8	1490.7	8093
-016	5.09	1.0-5.0		Uncooled SN 1		14.9	3.90	3.95	0	0.234	3.25	0.82	0	4.08	0.25	375.8	1534.2	7739
-017	5.08	1.0-3.3				20.1	2.57	2.59	0	0.517	3.76	1.45	0	5.22	0.20	384.3	2005.9	8139
-018	5.09	1.0-5.0				15.1	3.01	3.09	0	0.435	3.03	0.98	0	4.01	0.26	378.3	1518.0	7943
-019	5.09	1.0-3.4				14.8	2.00	2.02	0	0.488	2.59	1.29	0	3.89	0.27	378.1	1469.8	8052
-020	5.08	1.0-5.0				9.3	2.33	2.36	0	0.341	1.77	0.75	0	2.53	0.41	375.4	951.4	7739
-021	5.08	1.0-4.0				15.1	2.50	2.52	0	0.524	2.84	1.13	0	3.97	0.27	383.4	1523.0	8069
-022	5.09	1.0-5.0		Streak SN 2		15.7	3.16	3.20	0	0.413	3.05	0.95	0	4.02	0.29	378.2	1519.7	8246
-023				Film Cooled SN 1 10% 2.78" Ring		Sea Level Ignition Check												
-024	10.1	3.0-10.0				15.0	2.49	3.18	20.8	1.038	2.84	0.89	0.236	3.97	0.26	380.0	1510.0	7943
-025	10.1	3.0-10.0				14.8	2.47	2.80	10.1	1.110	2.75	0.98	0.122	3.86	0.28	400.5	1547.8	8069
-026	10.6	3.0-10.0				14.8	2.41	2.72	6.3	1.057	2.72	1.05	0.072	3.85	0.28	402.2	1546.5	8097
-027	10.1	3.0-10.0		20% 2.78" Ring		14.6	2.44	2.77	10.9	1.093	2.74	0.99	0.122	3.86	0.29	398.4	1537.9	7988
-028	10.1	3.0-10.0				16.1	2.47	3.16	21.0	1.167	2.78	0.88	0.236	3.90	0.26	429.3**	1675.2	8687
-029	10.1	3.0-10.0		20% 0.5" Ring		15.3	2.60	3.70	28.9	0.931	2.96	0.80	0.330	4.10	0.26	384.7	1578.0	7863
-030	10.1	3.0-10.0				15.3	2.52	2.86	20.9	1.045	2.86	0.89	0.237	3.99	0.25	400.4	1597.8	8064
-031	10.2	3.0-10.0				14.9	2.47	2.80	10.8	1.024	2.76	0.99	0.120	3.87	0.25	404.5	1567.5	8103
-032	10.1	3.0-10.0		10% 2.78" Ring	16/8	15.3	2.56	3.25	20.3	0.986	2.89	0.89	0.229	4.01	0.26	377.5	1513.6	8045
-033	10.1	3.0-10.0				14.6	2.44	2.76	10.7	1.076	2.74	0.99	0.120	3.86	0.26	394.1	1522.3	7950
-034	10.1	3.0-10.0				14.5	2.41	2.60	6.4	1.099	2.74	1.05	0.073	3.88	0.26	398.1	1546.1	7883

*Includes Igniter flow.

III, A, Program Progress (Tasks XI Through XX) (cont.)

For the second series of tests, the film coolant sleeve was removed and uncooled tests were conducted at three O/F ratios (2.0, 2.5, and 4) at the nominal 15 psia chamber pressure, followed by two tests at the chamber pressure extremes (10 and 20 psia) at a nominal 2.5 O/F ratio.

For the third series, the ablative lined chamber was installed and a 5-sec streak test was conducted without film cooling.

The fourth test series was conducted using the 2.78-in.-long 10% nominal design flow coolant ring. The effect of coolant injection velocity on coolant effectiveness will be available by comparing these results with the data from tests with the 2.78-in. 20% coolant ring previously tested. Coolant flows of 20, 10 and 5 percent of the fuel were used during these tests. The injector flow balance was adjusted for each test to provide a nominal overall engine O/F ratio of 2.5. These tests were conducted for a duration of 10 sec to improve the quality of the thermal data.

The fifth series of tests was a longer duration (10 sec) firing of the hardware tested in the first series. The overall engine O/F ratio was held at the nominal 2.5 during tests at 10 and 20 percent coolant flows.

The sixth series of tests continued the use of the 26 L* chamber but with a short 0.5-in.-long film coolant sleeve designed for optimum injection velocity at 20% coolant flow. This short coolant sleeve introduced the hydrogen coolant 0.5 in. from the injector face plane. As with the preceding coolant tests, the overall engine O/F ratio was held at 2.5 during coolant flows of 10, 20, and 30% of the total fuel.

The seventh, and final, series of tests evaluated the effect of L* and, to some extent, coolant injection station on performance and coolant effectiveness. The chamber L* was shortened to 16 in. and the 2.78-in.-long nominal 10% coolant sleeve was installed. This configuration then injected the coolant at the point where the chamber begins to converge toward the throat. As with the earlier tests using this coolant sleeve configuration, 20, 10 and 5 percent of the fuel was passed through the sleeve while the overall engine O/F was maintained at a nominal O/F ratio of 2.5. This concluded the revised injector test series.

c. Test Results

Testing was completed near the end of the reporting period and, therefore, data reduction and analysis are incomplete at this time. Preliminary data, which are available, are presented in the following paragraphs.

(1) Performance

The engine tests conducted during this period are tabulated on Table III-2. Although reduction and analysis of these data are incomplete, some encouraging results are apparent. Figure III-1 shows the delivered vacuum specific impulse for the four hardware configurations tested. These configurations are summarized below:

L*, in.	Coolant Sleeve Length, in.	Coolant Sleeve Design Flow Rate, % Fuel for $V_{coolant} = V_{comb.\ prod}$
26	2.78	10
26	2.78	20
26	0.5	20
16	2.78	10

The effect of the reduced L* is shown to reduce performance by approximately 5 sec for coolant fractions between 6 and 20% of the total fuel. A shorter length coolant sleeve results in an increase in delivered specific impulse of over 7 sec for coolant fractions between 10 and 30% of the total fuel flow, probably due to increased mixing and heating of the hydrogen coolant.

LOW P_c O_2/H_2 APS ENGINE
PRELIMINARY PERFORMANCE DATA

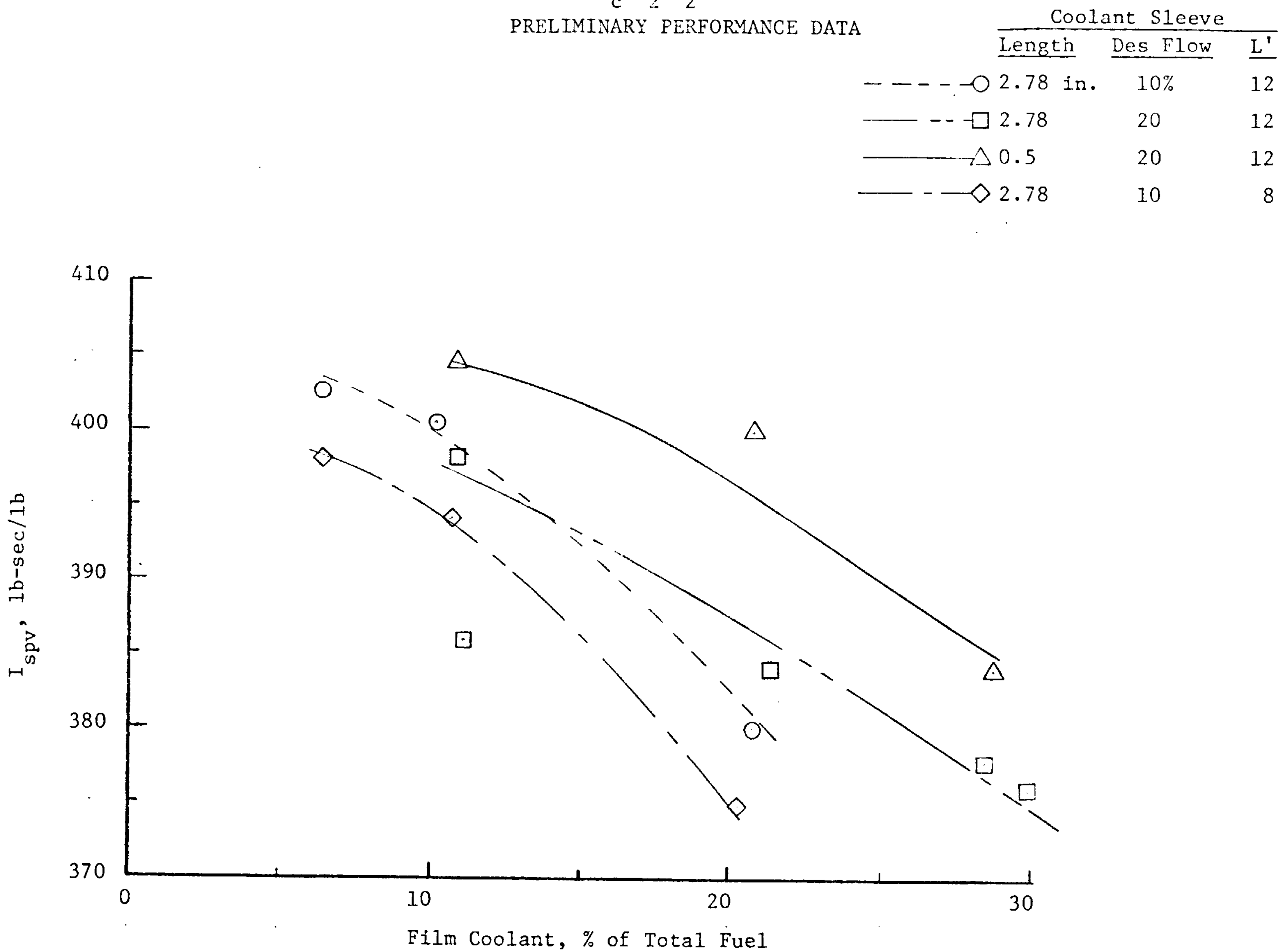

Figure III-1

Comparison of the performance and thermal data to identify the optimum operating condition for this engine and a more detailed performance loss analysis will be completed in the next report period.

(2) Heat Transfer

Heat transfer data were obtained in the form of inside wall temperatures and gas probe temperatures at several locations in the chamber. The wall temperature data are being analyzed using a finite difference thermal analyzer computer program (SINDA) and heat flux-wall temperature curves are generated from which recovery temperature is determined. Figure III-2 shows recovery temperatures for three test conditions. The gas temperature probes at the throat station recorded the temperatures shown on Figure III-3 for three coolant sleeve configurations at various coolant flows. From the early data, it appears that the results obtained were as expected. A more complete reporting of the results of the data analysis will be included in next month's report.

9. Task XIX - Cooled Chamber Testing

No activity during this period.

10. Task XX - Pulse Testing

No activity during this period.

B. CURRENT PROBLEMS

No significant problems have been encountered.

LOW P_c O_2/H_2 APS ENGINE
EFFECT OF COOLANT QUANTITY ON RECOVERY TEMPERATURE
(Injection Velocity Ratio = 1)

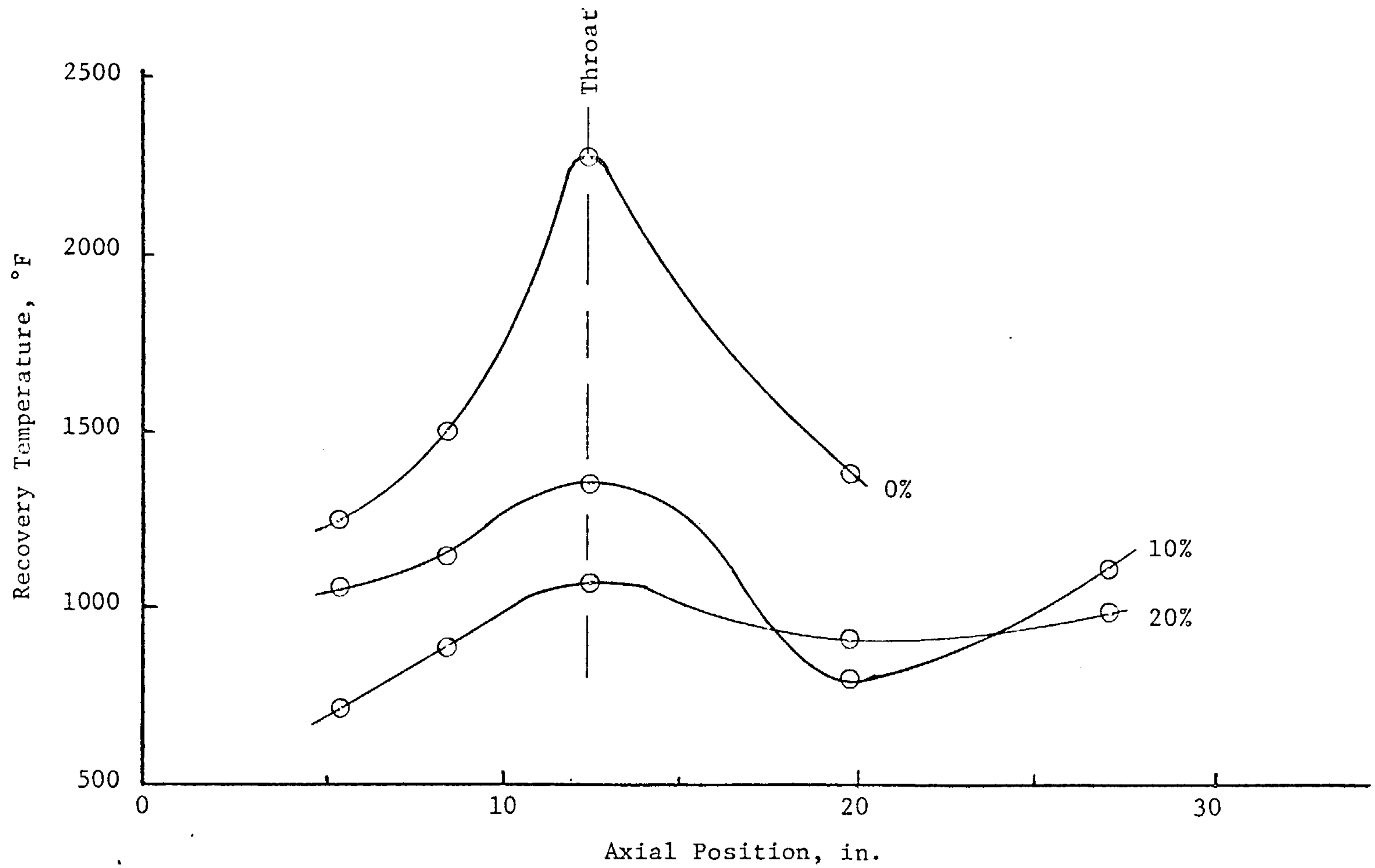

Figure III-2

LOW P_c O_2/H_2 APS ENGINE

EFFECT OF COOLANT QUANTITY AND INJECTION GEOMETRY ON BARRIER PROBE TEMPERATURES AT THE THROAT

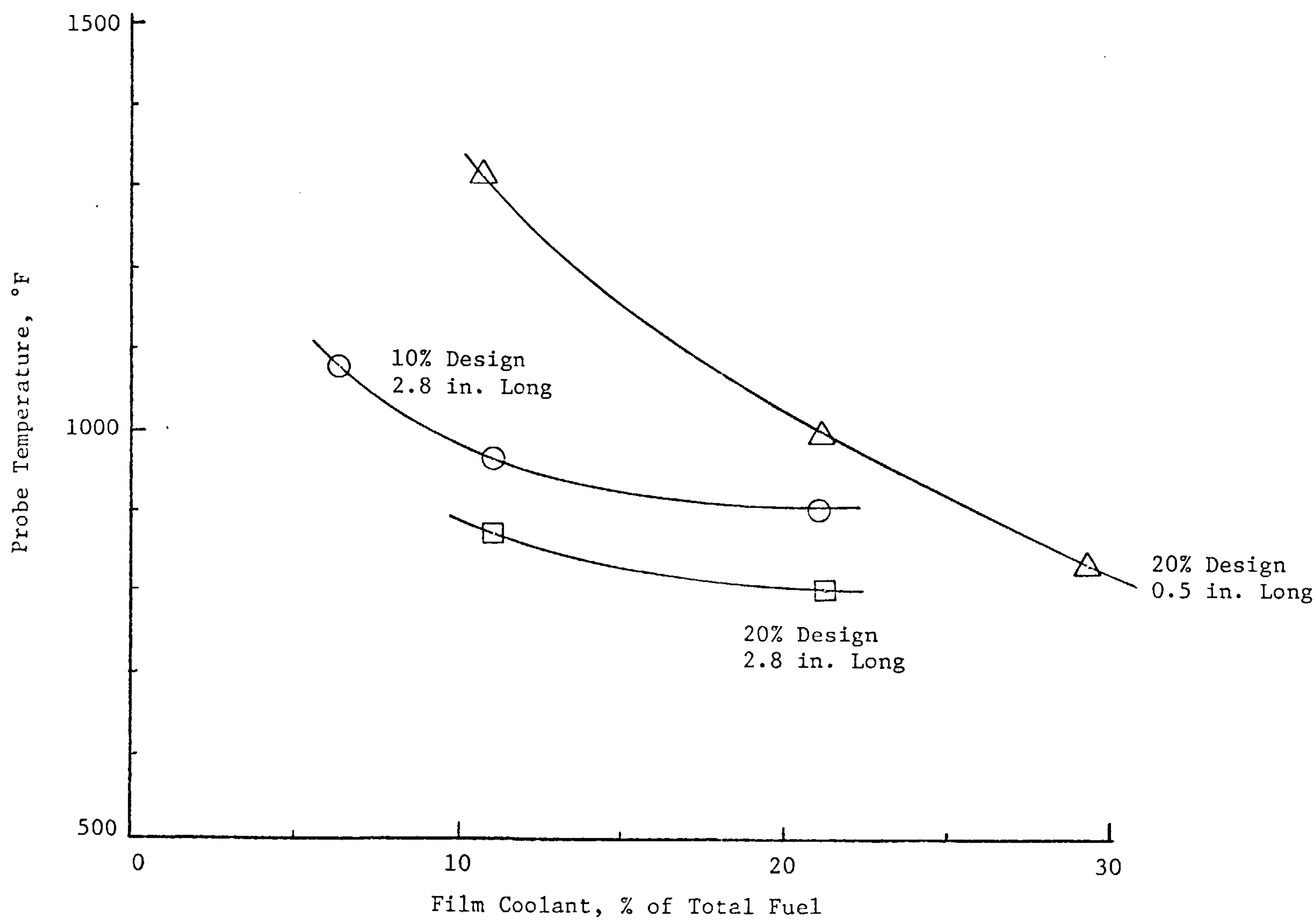

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Figure III-3

III, Low Pressure Technology Program (cont.)

C. WORK TO BE PERFORMED IN THE NEXT REPORT PERIOD

1. <u>Task XI - Injector Analysis and Design</u>

   All effort stopped on this task.

2. <u>Task XII - Injector Fabrication</u>

   All effort stopped on this task.

3. <u>Task XIII - Thrust Chamber Analysis and Design</u>

   All effort stopped on this task.

4. <u>Task XIV - Thrust Chamber Fabrication</u>

   All effort stopped on this task.

5. <u>Task XV - Catalytic Igniter Analysis and Design</u>

   Completed.

6. <u>Task XVI - Catalytic Igniter Fabrication and Checkout</u>

   Conduct ambient temperature and cold propellant tests.

7. <u>Task XVII - Propellant Valve Preparation</u>

   All effort stopped on this task.

8. <u>Task XVIII - Injector Testing</u>

   Complete the reduction, analysis and documentation of test data.

III, C, Work to be Performed in the Next Report Period (cont.)

9. Task XIX - Cooled Chamber Tests

No activity planned.

10. Task XX - Pulsing Tests

No activity planned.

FORECAST AND CONSUMPTION OF GOVERNMENT-FURNISHED PROPELLANTS

Contract NAS 3-14354

Material	Monthly Usage	Cumulative	Next Month's Requirements	Next 3 Months' Requirements
LO_2 (ton)	0	0	0	28
LH_2 (lb)	1930	3268	0	0
LN_2 (ton)	58.7	165.9	30	260
GHe (SCF)	0	99,100	50	12,550